SIXTY YEARS OF EXPERIMENTAL SUPERSONIC RESEARCH

(Presented before the Dayton Section of the Institute of the Aeronautical Sciences
June 25, 1948
by Hugh L. Dryden, Director of Aeronautical Research
National Advisory Committee for Aeronautics)

The lecture was based on the following notes on the history of supersonic wind tunnels:

Introduction

New words -- subsonic, transonic, supersonic, hypersonic
Early terms -- subacoustic, acoustic, hyperacoustic
Supersonic speeds long familiar -- meteorites, bullets, projectiles.
Oldest experimental data from ballistics (firing experiments).
Supersonic wind tunnels dependent on De Laval nozzle used by De Laval who developed first successful steam turbine in 1884. De Laval nozzle has converging section to throat followed by diverging section, permitting expansion from sonic speed at the throat to supersonic speeds at the exit.

Ernst Mach

Ernst Mach, born February 18, 1838, studied at Vienna. Dr. Phil. 1860, Professor of Physics at University of Prague 1867-1895, Professor of Philosophy at University of Vienna 1896-1901. Retired in 1901, died in 1916. Many contributions to optics, outstanding books on heat, mechanics, etc.

In 1887 Mach presented paper with P. Salcher to the Vienna Academy of Sciences entitled "Photographic Registration of the Phenomena in the Air Produced by a Projectile." This paper contains first photographs of shock waves at the nose of a projectile. (Akad. Wiss. Wien 95:764, 1887).

In 1889 Mach and Salcher presented a second paper entitled "Optical Study of Air Jets," (Akad. Wiss. Wien 98 II:267, 1889). The following is quoted from this paper: "On the occasion of the experiments on projectiles Salcher hit upon the idea of likewise investigating the converse case of the flow of air against a body at rest in order to confirm the results already obtained. The possibility of conducting such experiments arose through the friendly cooperation of Messrs. John Whitehead who placed at our disposal space and supplies for the experiments in the torpedo factory at Fiume. -----. Since it was found that the experimental results obtained by Salcher stood in a certain relation to the experiments previously conducted by Mach and since further all the desired experimental set-ups could not be made in the factory at Fiume, we joined our efforts and E. Mach carried out with the cooperation of medical student L. Mach, to whom all the technical work fell, a series of experiments in Prague."

Ludwig Mach, born November 18, 1868, at Prague, was the son of Ernst Mach. He studied medicine at Prague 1888-1893 and received a degree of Doctor of Medicine in 1895. Ludwig Mach first photographed shock waves in a free jet in these experiments conducted as a favor to his father.

The supersonic jets were round, 1.2 to 5.2 mm. in diameter, 2 mm. square, and 1 by 10 mm. rectangular cross section. The pressures were 60 to 70 atmospheres, the duration of flow 3 to five seconds, the time required to pump up the reservoir 10 minutes.

E. Mach later with Zehnder (1891) developed the Mach-Zehnder interprometer for studying air flow.

A photograph of E. Mach and a tribute to him by Einstein is to be found in the Physikalische Zeitschrift, vol. 17, 1916.

Early French Experiments

In 1916 the French physicist Langevin became interested in supersonic jets as a means of testing a new type of projectile invented by the French inventor Chilowsky. In 1917 the task was taken up by Huguenard and Sainte-Legue, who decided to look for some existing compressed-air plant. They state, "There are two large compressed-air stations in the world: the one belonging to the Compagnie Parisienne de l'Air Comprimé which has compressors with a total power of 12,000 horsepower supplying air at a pressure of about 6½ atmospheres and a temperature of 40 degrees C; the other of 100,000 horsepower is at the Rand mines in South Africa."

The Paris installation was nearest. The plant was used to supply air for a pneumatic system for transferring mail from one post office to another in the City of Paris. Huguenard and Sainte-Legue used a tank of about 7 cubic meters capacity. The nozzle had an 80-mm. throat and was 120 mm. in diameter at the exit. Langevin thought that he had a Mach number of 1.35, but actually it was only 1.07 because of separation in the diffuser. The nozzle was rebuilt to have an exit diameter of 98 mm (6° angle), and a Mach number of about 1.4 was obtained.

These experimenters proposed to build a true high-speed laboratory but plans were abandoned after the Armistice. The plans included preheating of the air. (La Technique Aeronautique, Nov. and Dec. 1924. NACA Technical Memorandum No. 318.)

The following remarks of Huguenard are of interest: "Alone among all the methods of transportation, aviation has shown, from its very beginning, an extraordinarily rapid increase in speed. From about 49 ft/sec in the first flights, we have progressed in 27 years to more than 394 ft/sec, the speed doubling regularly every five or six years. This is certainly not accidental. At each new performance, pessimistic calculators, accepting with more or less grace the results already obtained and arming themselves with formulas borrowed from other modes of locomotion, have somewhat advanced the limit they had previously set to the speed of aircraft, whereupon this new limit has been promptly exceeded. Since there is no indication of any change in the speed curve (aside from technical considerations, which have thus far amounted to nothing) we must logically expect aircraft to attain speeds of the order of 787 ft/sec within five or six years. The high-velocity wind tunnel will doubtless be an important factor in solving the problem as to what new means of propulsion will be required."

In Huguenard's work we see the change in motivation for high-speed research from ballistics to aeronautical problems. Interest in the aerodynamic characteristics of propellers at high tip speeds was the first practical problem of interest.

From 1920 to 1935, year of the Volta Congress

1920 Caldwell and Fales (NACA TR 83) reported measurements on propeller sections in the 200-horsepower, one-foot, McCook Field wind tunnel at Mach numbers up to 0.5.

1922 Douglas and Word (British ARC RM 884) described measurements of propeller performance at high tip speeds, from which airfoil characteristics at high speeds were computed.

1923-1930 Briggs, Hull, and Dryden (NACA TR 207, 255, 319, 365) carried out measurements on airfoils at high speeds. The first experiments were conducted at Lynn Works of the General Electric Company on discharge from compressor intended for Bessemer steel converter while compressor was under acceptance test. Three-stage centrifugal compressor, 5000 hp., 50,000 c.f.m., 15 lb/in^2 pressure. Nozzle 12 inches in diameter, measurements in open jet up to Mach number of 0.95. Oil placed on the steel airfoils to prevent rusting moved under the influence of the stream in pattern showing separation of flow at high speeds even at small angles of attack. Lift, drag, and center-of-pressure measurements were made.

The experiments were continued at Edgewood Arsenal using a compressor plant which had been used during the war to fill gas shells. The plant included four double-acting reciprocating compressors, 1800 c.f.m. up to 125 lbs. pressure. Two inch nozzles were used, of the De Laval type for supersonic speeds, up to a Mach number of 1.08. The same nozzles were later used with another compressor at the National Bureau of Standards.

1928 T. E. Stanton (British ARC RM 1130, 1210, 1280) made measurements in a three-inch jet up to Mach numbers of 1.7 on cylinders and airfoils. 530 hp required to furnish the air stream.

1928 Busemann (Jahrbuch Wissen. Gesell f. Luftfahrt, 1928, p. 96) describes equipment at Gottingen used by Ackeret and himself under Prandtl's direction. An intermittent-flow wind tunnel, 6 cm by 6 cm, 10 sec. duration from 10 m^3 tank with subsonic nozzle to choking Mach number. He states: "Of our own measurements there are only available sufficient that we can determine the general operation of our apparatus. In order to show what kind of results are to be expected therefore, some examples will be given from the American literature."

J. Ackeret, born 1898 at Zurich, assistant to Stodola, at Gottingen 1921-26, to Zurich in 1927.

A. Busemann, born 1901, at Gottingen with Prandtl in 1925.

1928 (?) Ackeret designed and had constructed by Brown-Boveri a continuous-flow supersonic wind tunnel, 1000 hp, 13-stage axial-flow compressor of 2.4 compression ratio. Working section, 40 x 40 cm. Highest Mach number, 2. Description of this first modern supersonic wind tunnel published in 1935 (NACA TM 808).

1929 W. Margoulis submitted project for 0.8 m supersonic tunnel for Mach number of 3.5 to French government. 700 hp, reduced density. (Journees Scientifique et Techniques de Mecanique des Fluides tenues a Lille en 1934. Chiron, Paris, 1935).

Margoulis, collaborator of Joukowsky, born in Russia, lived in France after 1913 and directed the Eiffel Laboratory in the first World War. In 1920 considered reduced density to save power, proposed various designs, i.e.

Mach number 0.8,	propeller tests,	2 m diameter,	2000 hp
1.4,	airfoil tests,	1 m diameter,	1000 hp
3.0,	airfoil tests,	0.3 m diameter,	1100 hp

French government authorized a tunnel 8 cm working section, Mach number 2.7, 50 horsepower, completed in 1933 at the University of Paris. Other French experimenters were Villat, Tremblot, Dupuy, and Santon in a 5 cm by 10 cm wind tunnel of Mach number 2.2.

1933 John Stack constructed 24-inch wind tunnel driven from 20-atmosphere pressure tank of variable-density wind tunnel at the Langley Laboratory of NACA.

1935 The Guidonia Laboratory was under construction in Italy, directed by General G. A. C. Ferrari. The working section was 40 cm by 40 cm, Mach number 2.7, 2500 to 3000 horsepower, density at end of diffuser, about 1/7 atmosphere.

From 1935 (Volta Congress) to 1948

From September 30 to October 6, 1935, the Volta Congress on High Speeds in Aviation was held in Rome under sponsorship of the Italian government. U.S. delegates were E. N. Jacobs of NACA and Th. von Kármán of California Institute of Technology. Leading workers of all countries were present and the state of the art reviewed. This Congress may be taken as the starting point of a more vigorous interest in and development of supersonic wind tunnels which will be summarized briefly by countries.

Germany

Dresden, 1935	Busemann developed 300 hp, 17cm diameter, and 25 cm x 25 cm wind tunnel, Mach number up to choking.
Aachen, 1935	Open jet, 10 cm x 11.7 cm, M = 3.16 intermittent (made closed return and continuous in 1941).
1938	20 cm x 20 cm, M = 3.16, intermittent
1942	8 cm x 12 cm, M = 2.9, intermittent
LFA Braunschweig, 1936	25 cm x 25 cm, M = 3, continuous
1938	25 cm diameter, M = 3, intermittent
1939	2.8 meters diameter, M = 1, 12,000 kw, continuous (the wind tunnel in which the buzz-bomb motor was perfected).
1943	1 meter diameter, M = 1, continuous
1943	0.94 meter x 0.94 meter, M = 1.82, continuous
Göttingen, 1939	11 x 13 cm, M = 3.2, 150 kw, intermittent
Peenemunde, 1941	40 cm x 40 cm, M = 4.4, intermittent (later removed to Kochel).

Under construction at the end of the war were:

Kochel, 1 meter by 1 meter, M = 7 to 10, 76,000 hp.
Ötztal, 8 meters diameter, M = 1, 100,000 hp.
LFM, Munich, 3 meters diameter, M = 1, 10,000 kw.
" 40 cm by 40 cm, M = 2.8, continuous.
" 25 cm by 25 cm, M = 3.2, intermittent.

United States

Kármán proposed the construction of a supersonic wind tunnel to the Ordnance Department of the Army in 1939. April 9, 1940, the Ordnance Department requested the National Academy of Sciences to appoint a committee to make recommendations. June 24, 1940, the committee was appointed, consisting of W. F. Durand, Gano Dunn, H. L. Dryden, and F. Moulton. The committee on July 20 reported favorably, recommending design study and model at California Institute of Technology. The model constructed was 2.5 inches square, 200 hp, and intended to reach Mach numbers of 3.2 to 4.6. The committee was reconvened in February 1942, and recommended construction of the larger tunnel, which after some delay was built at Aberdeen Proving Ground. The 15-inch by 20-inch wind tunnel of 13,000 hp was first operated in December 1944, and dedicated May 1945.

The NACA built a 9-inch supersonic wind tunnel in 1944, a 1-ft. by 3-ft. in 1945, and a 1-ft by $3\frac{1}{2}$-ft. in 1946, the first at Langley, the others at Ames Laboratory. There are now coming into operation a 4-ft. by 4-ft. wind tunnel at Langley, a 6-ft. by 6-ft. at Ames, and a 6-ft. by 8-ft. at the Flight Propulsion Research Laboratory at Cleveland.

The British built a tunnel operating from the compressed air tunnel, similar to Stack's wind tunnel at Langley.

The French built several wind tunnels 9 cm by 18 cm, 9 cm by 11 cm, etc., for Mach numbers of 2 to 3.5.

History of the term "Mach number"

The term Mach number was suggested by J. Ackeret in a paper entitled "Air Resistance at Very High Speeds," appearing in Schweizerische Bauzeitung, 94:179, 1929. In a foot note he says: "In high-speed aerodynamics the ratio V/a continually recurs. It is therefore desirable to introduce a shorter symbol. Since the well-known physicist E. Mach clearly recognized the fundamental significance of this ratio in our field and confirmed it by clever experimental methods, it appears to be justified to denote V/a as the Mach number."

Mach number is preferred to Mach's number. It is interesting to note that this usage was not fully accepted six years later at the Volta Congress. Ackeret, Busemann, and Pistolesi used M, but Prandtl used u/c, Jacobs used V/Vc, and Kármán used V/a. Shortly afterward, however, the usage became almost universal.

Many recent French books use the designation Sarrau number after Jacques Rose Ferdinand Emile Sarrau who succeeded St. Venant as a member of the French Academy in 1886. Sarrau, born June 24, 1837, died 1904, was director of the Central Depot de Pulver et Saltpeter, and professor of mechanics at the École Polytechnique. Strange as it may seem, the symbol for the Sarrau number is M.